6. Land-Use Change and Forestry

This chapter provides an assessment of the net carbon dioxide (CO_2) flux caused by changes in forest carbon stocks (trees, understory, forest floor, forest soil, wood products, and landfilled wood), and a preliminary assessment of the net CO_2 flux caused by changes in non-forest soil carbon stocks. Unlike the assessments in other chapters, which are based on annual activity data, estimates for the Land-Use Change and Forestry chapter are based on periodic activity data in the form of forest, wood product, and landfilled wood surveys. As a result, the CO_2 flux from forest carbon stocks was calculated on an average annual basis. This annual average value was then applied to the years between surveys. In addition, because the most recent national compilation of state forest surveys was completed for the year 1992, and the most recent wood product and landfilled wood surveys were completed for the year 1990, the estimates of the CO_2 flux from forest carbon stocks are based in part on modeled projections of stock estimates for the year 2000.

Carbon dioxide fluxes caused by changes in forest floor, forest soil, and non-forest soil carbon stocks were not assessed in previous U.S. greenhouse gas inventories due to insufficient data and lack of accepted guidelines. The assessment of CO_2 flux from forest floor and forest soil carbon stocks in this inventory was based on stock estimates developed by the U.S. Forest Service, and is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The assessment of CO_2 flux from non-forest soils was based on the *Revised 1996 IPCC Guidelines*, which includes methodologies for calculating non-forest soil carbon flux from three land-use practices: (1) cultivation of mineral soils, (2) cultivation of organic soils, and (3) liming of agricultural soils. However, due to insufficient data about these land-use activities in the United States, this chapter provides only a preliminary assessment of CO_2 fluxes from two of the three land-use practices: cultivation of organic soils and liming of agricultural soils. Because of the high level of uncertainty associated with these two flux estimates, and the lack of a flux estimate for the third activity, the non-forest soil flux estimates have not been incorporated into the total fluxes reported for the Land-Use Change and Forestry chapter.

See Table 6-1 and Table 6-2 for a summary of CO_2 fluxes estimated from Land-Use Change and Forestry in the United States.

Changes in Forest Carbon Stocks

Globally, the most important human activity that affects forest carbon fluxes is deforestation, particularly the clearing of tropical forests for agricultural use. Tropical deforestation is estimated to have released nearly 6 billion metric tons of CO_2 per year during the 1980s, or about 23 percent of global CO_2 emissions from anthropogenic

Table 6-1: Net CO_2 Flux from Land-Use Change and Forestry (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996	1997
Forests	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)
Soil	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)
Harvested Wood	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Wood Products	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Landfilled Wood	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Total Net Flux*	**(311.5)**	**(311.5)**	**(311.5)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes preliminary flux estimates for non-forest soils due to the high level of uncertainty of these estimates.

Table 6-2: Net CO_2 Flux from Land-Use Change and Forestry (Tg CO_2)

Description	1990	1991	1992	1993	1994	1995	1996	1997
Forests	**(1,005.4)**	**(1,005.4)**	**(1,005.4)**	**(627.9)**	**(627.9)**	**(627.9)**	**(627.9)**	**(627.9)**
Trees	(350.5)	(350.5)	(350.5)	(271.3)	(271.3)	(271.3)	(271.3)	(271.3)
Understory	(8.8)	(8.8)	(8.8)	(4.6)	(4.6)	(4.6)	(4.6)	(4.6)
Forest Floor	(76.3)	(76.3)	(76.3)	(35.8)	(35.8)	(35.8)	(35.8)	(35.8)
Soil	(569.1)	(569.1)	(569.1)	(316.3)	(316.3)	(316.3)	(316.3)	(316.3)
Harvested Wood	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**
Wood Products	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)
Landfilled Wood	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)
Total Net Flux*	**(1,142.2)**	**(1,142.2)**	**(1,142.2)**	**(764.7)**	**(764.7)**	**(764.7)**	**(764.7)**	**(764.7)**

Note: Parentheses indicate sequestration. Totals may not sum due to independent rounding. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.
*The total net flux excludes preliminary flux estimates for non-forest soils due to the high level of uncertainty of these estimates.

activities. Conversely, during this period about 7 percent of global CO_2 emissions were offset by CO_2 uptake due to forest regrowth in the Northern Hemisphere (Houghton et al. 1995).

In the United States, the amount of forest land has remained fairly constant during the last several decades. The United States covers roughly 2,263 million acres, of which 33 percent (737 million acres) is forest land (Powell et al. 1993). The amount of forest land declined by approximately 5.2 million acres between 1977 and 1987 (USFS 1990, Waddell et al. 1989), and increased by about 5.3 million acres between 1987 and 1992 (Powell et al. 1993). These changes represent average fluctuations of only about 0.1 percent per year. Other major land-use categories in the United States include range and pasture lands (29 percent), cropland (17 percent), urban areas (3 percent), and other lands (18 percent) (Daugherty 1995).

Given the low rate of change in U.S. forest land area, the major influences on the current net carbon flux from forest land are management activities and ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density of the forest, thereby increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils.

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- Trees (i.e., living trees, standing dead trees, roots, stems, branches, and foliage)

- Understory vegetation (i.e., shrubs and bushes)
- The forest floor (i.e., woody debris, tree litter, and humus)
- Soil

As a result of biological processes in forests (e.g., growth and mortality) and anthropogenic activities (e.g., harvesting, thinning, and replanting), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage of carbon in living biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the forest carbon pools over time.

The net change in forest carbon, however, may not be equivalent to the net flux between forests and the atmosphere because timber harvests may not always result in an immediate flux of carbon to the atmosphere.[1] Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 if the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested for energy use, combustion results in an immediate release of carbon. Conversely, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If wood products are disposed of in landfills, the carbon contained in the wood may be released years or decades later, or may even be stored permanently in the landfill.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in an annual net uptake (i.e., sequestration) of carbon. Also due to improvements in U.S. agricultural productivity, the rate of forest land clearing for crop cultivation and pasture slowed in the late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested. The impacts of these land-use changes are still affecting carbon fluxes from forests in the East. In addition to land-use changes in the early part of this century, in recent decades carbon fluxes from Eastern forests were affected by a trend toward managed growth on private land, resulting in a near doubling of the biomass density in eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on reforesting previously harvested lands, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net carbon fluxes. Because most of the timber that is harvested from U.S. forests is used in wood products and much of the discarded wood products are disposed of by landfilling—rather than incineration—significant quantities of this harvested carbon are transferred to long-term storage pools rather than being released to the atmosphere. The size of these long-term carbon storage pools has also increased steadily over the last century.

As shown in Table 6-3 and Table 6-4, U.S. forest components, wood product pools, and landfill wood were estimated to account for an average annual net sequestration of 311.5 MMTCE (1,142.2 Tg CO_2) from 1990 through 1992, and 208.6 MMTCE (764.7 Tg CO_2) from 1993 through 1997. The net carbon sequestration reported for 1997 represents an offset of about 14 percent of the 1997 CO_2 emissions from fossil fuel combustion. The average annual net carbon sequestration reported for 1993 through 1997 represents a 33 percent decrease relative

[1] For this reason, the term "apparent flux" is used in this chapter.

Table 6-3: Net CO_2 Flux from U.S. Forests (MMTCE)

Description	1990	1991	1992	1993	1994	1995	1996	1997
Apparent Forest Flux	**(274.2)**	**(274.2)**	**(274.2)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**	**(171.3)**
Trees	(95.6)	(95.6)	(95.6)	(74.0)	(74.0)	(74.0)	(74.0)	(74.0)
Understory	(2.4)	(2.4)	(2.4)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Forest Floor	(20.8)	(20.8)	(20.8)	(9.8)	(9.8)	(9.8)	(9.8)	(9.8)
Forest Soils	(155.2)	(155.2)	(155.2)	(86.3)	(86.3)	(86.3)	(86.3)	(86.3)
Apparent Harvested Wood Flux	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**	**(37.3)**
Apparent Wood Product Flux	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)	(17.9)
Apparent Landfilled Wood Flux	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)	(19.4)
Total Net Flux	**(311.5)**	**(311.5)**	**(311.5)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**	**(208.6)**

Note: Parentheses indicate net carbon "sequestration" (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word "apparent" is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 6-4: Net CO_2 Flux from U.S. Forests (Tg CO_2)

Description	1990	1991	1992	1993	1994	1995	1996	1997
Apparent Forest Flux	**(1,005.4)**	**(1,005.4)**	**(1,005.4)**	**(627.9)**	**(627.9)**	**(627.9)**	**(627.9)**	**(627.9)**
Trees	(350.5)	(350.5)	(350.5)	(271.3)	(271.3)	(271.3)	(271.3)	(271.3)
Understory	(8.8)	(8.8)	(8.8)	(4.6)	(4.6)	(4.6)	(4.6)	(4.6)
Forest Floor	(76.3)	(76.3)	(76.3)	(35.8)	(35.8)	(35.8)	(35.8)	(35.8)
Forest Soils	(569.1)	(569.1)	(569.1)	(316.3)	(316.3)	(316.3)	(316.3)	(316.3)
Apparent Harvested Wood Flux	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**	**(136.8)**
Apparent Wood Product Flux	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)	(65.5)
Apparent Landfilled Wood Flux	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)	(71.2)
Total Net Flux	**(1,142.2)**	**(1,142.2)**	**(1,142.2)**	**(764.7)**	**(764.7)**	**(764.7)**	**(764.7)**	**(764.7)**

Note: Parentheses indicate net carbon "sequestration" (i.e., sequestration or accumulation into the carbon pool minus emissions or harvest from the carbon pool). The word "apparent" is used to indicate that an estimated flux is a measure of net change in carbon stocks, rather than an actual flux to or from the atmosphere. The sum of the apparent fluxes in this table (i.e., total flux) is an estimate of the actual flux. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

to the average annual net carbon sequestration reported for 1990 through 1992. This overall decrease in annual net sequestration was due to changes in the aggregate age structure of U.S. forests caused by the maturation of existing forests and the slowed expansion of Eastern forest cover. The abrupt shift in annual net sequestration from 1992 to 1993 is the result of calculating average annual fluxes using periodic activity data as well as models that estimate and project decadal rather than annual stock estimates.

Methodology

The methodology for estimating annual forest carbon flux in the United States differs from the methodologies employed for other sources because the forest carbon flux estimates for this source were derived from periodic surveys of forest carbon stocks rather than annual activity data. Three surveys of forest carbon stocks were used: (1) timber stocks, (2) wood products, and (3) landfilled wood. In addition, because national compilations of state forest surveys have not been completed for 1997, projections of forest carbon stocks, rather than complete historical data, were used to derive some of the annual flux estimates.

Timber stock data from forest surveys were used to derive estimates of carbon contained in the four forest ecosystem components (trees, understory, forest floor, and soil) for the survey years. The apparent annual forest carbon flux for a specific year was estimated as the average annual change in the total forest carbon stocks between the preceding and succeeding timber survey years. The most recent national compilations of state forest surveys were conducted for the years 1987 and 1992, and a projection has been prepared for the year 2000. Therefore, the apparent annual forest carbon flux estimate for the years 1990 through 1992 was calculated from forest carbon stocks reported for 1987 and 1992, and the apparent annual forest carbon flux estimate for the years 1993 through 1997 was calculated from forest carbon stocks for 1992 and projected forest carbon stocks for the year 2000.

Carbon stocks contained in the wood product and landfilled wood pools were estimated for 1990 using historical forest harvest data, and were estimated for 2000 using projections of forest harvest. Therefore, apparent annual wood product and landfilled wood fluxes for the years 1990 through 1997 were calculated from a 1990 historical estimate and a 2000 projection.

The total annual net carbon flux from forests was obtained by summing the apparent carbon fluxes associated with changes in forest stocks, wood product pools, and landfilled wood pools.

The inventory methodology described above is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). The IPCC identifies two approaches to developing an emissions inventory for Land-Use Change and Forestry: (1) using average annual statistics on land-use change and forest management activities, and applying carbon density and flux rate data to these activity estimates to derive total flux values; or (2) using carbon stock estimates derived from periodic inventories of forest stocks, and measuring net changes in carbon stocks over time. The latter approach was employed because the United States conducts periodic surveys of national forest stocks. In addition, the IPCC identifies two approaches to accounting for carbon emissions from harvested wood: (1) assuming that all of the harvested wood replaces wood products that decay in the inventory year so that the amount of carbon in annual harvests equals annual emissions from harvests; or (2) accounting for the variable rate of decay of harvested wood according to its disposition (e.g., product pool, landfill, combustion). The latter approach was applied for this inventory using estimates of carbon stored in wood products and landfilled wood.[2] Although there are large uncertainties associated with the data used to develop the flux estimates presented here, the use of direct measurements from forest surveys and associated estimates of product and landfilled wood pools is likely to result in more accurate flux estimates than the alternative IPCC methodology.

Data Sources

The estimates of forest, product, and landfill carbon stocks used in this inventory to derive carbon fluxes were obtained from Birdsey and Heath (1995), Heath et al. (1996), and Heath (1997). The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 1987 and 1992 was estimated using timber volume data collected by the U.S. Forest Service (USFS) for those years (Waddell et al. 1989, Powell et al. 1993). The timber volume data include timber stocks on forest land classified as timberland, reserved forest land, or other forest land[3] in the contiguous United States, but do not include stocks on forest land in Alaska, Hawaii, U.S. territories, or trees on non-forest land (e.g., urban trees).[4] The timber volume data include estimates by tree species, size class, and other categories.

The amount of carbon in trees, understory vegetation, the forest floor, and forest soil in 2000 was estimated by Birdsey and Heath (1995) using the FORCARB forest carbon model (Plantinga and Birdsey 1993) linked

[2] This calculation does not account for carbon stored in imported wood products. It does include carbon stored in exports, even if the logs are processed in other countries (Heath et al. 1996).

[3] Forest land in the U.S. includes all land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, growing at a rate of 20 cubic feet per acre per year or more. In 1992, there were about 490 million acres of Timberlands, which represented 66 percent of all forest lands (Powell et al. 1993). Forest land classified as Timberland is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 34 percent of forest land is classified as Productive Reserved Forest Land, which is withdrawn from timber use by statute or regulation, or Other Forest Land, which includes unreserved and reserved unproductive forest land.

[4] Although forest carbon stocks in Alaska and Hawaii are large compared to the U.S. total, net carbon fluxes from forest stocks in Alaska and Hawaii are believed to be minor. Net carbon fluxes from urban tree growth are also believed to be minor.

to the TAMM/ATLAS forest sector model (Adams and Haynes 1980, Alig 1985, Haynes and Adams 1985, Mills and Kincaid 1992). The forest stock projections for 2000, therefore, are based on multiple variables, including projections of prices, consumption, and production of timber and wood products; and projections of forest area, forest inventory volume, growth, and removals.

The amount of carbon in aboveground and belowground tree biomass in forests was calculated by multiplying timber volume by conversion factors derived from studies in the United States (Cost et al. 1990, Koch 1989). Carbon stocks in the forest floor and understory vegetation were estimated based on simple models (Vogt et al. 1986) and review of numerous intensive ecosystem studies (Birdsey 1992). Soil carbon stocks were calculated using a model similar to Burke et al. (1989) based on data from Post et al. (1982).

Carbon stocks in wood products in use and in wood stored in landfills were estimated by applying the HARVCARB model (Row and Phelps 1991) to historical harvest data from the USFS (Powell et al. 1993) and harvest projections for 2000 (Adams and Haynes 1980, Mills and Kincaid 1992). The HARVCARB model allocates harvested carbon to disposition categories (products, landfills, energy use, and emissions), and tracks the accumulation of carbon in different disposition categories over time.

Table 6-5 presents the carbon stock estimates for forests (including trees, understory, forest floor, and forest soil), wood products, and landfilled wood used in this inventory. The increase in all of these stocks over time indicates that, during the examined periods, forests, forest product pools, and landfilled wood all accumulated carbon (i.e., carbon sequestration by forests was greater than carbon removed in wood harvests and released through decay; and carbon accumulation in product pools and landfills was greater than carbon emissions from these pools by decay and burning).

Table 6-5: U.S. Forest Carbon Stock Estimates[5] (Tg of Carbon)

Description	1987	1990	1992	2000
Forests	**36,353**	**NA**	**37,724**	**39,094**
Trees	13,009	NA	13,487	14,079
Understory	558	NA	570	580
Forest Floor	2,778	NA	2,882	2,960
Forest Soil	20,009	NA	20,785	21,475
Harvested Wood	**NA**	**3,739**	**NA**	**4,112**
Wood Products	NA	2,061	NA	2,240
Landfilled Wood	NA	1,678	NA	1,872

NA (Not Available)
Note: Forest carbon stocks do not include forest stocks in Alaska, Hawaii, U.S. territories, or trees on non-forest land (e.g., urban trees); wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Uncertainty

There are considerable uncertainties associated with the estimates of the net carbon flux from U.S. forests. The first source of uncertainty stems from the underlying forest survey data. These surveys are based on a statistical sample designed to represent a wide variety of growth conditions present over large territories. Therefore, the actual timber volumes contained in forests are represented by average values that are subject to sampling and estimation errors. In addition, the forest survey data that are currently available exclude timber stocks on forest land in Alaska, Hawaii, U.S. territories, and trees on non-forest land (e.g., urban trees); however, net carbon fluxes from these stocks are believed to be minor.

The second source of uncertainty results from deriving carbon storage estimates for the forest floor, understory vegetation, and soil from models that are based on data from forest ecosystem studies. In order to extrapolate results of these studies to all forest lands, it was assumed that they adequately describe regional or national averages. This assumption can potentially introduce the following errors: (1) bias from applying data

[5] Sources: Heath (1997), Heath et al. (1996), and Birdsey and Heath (1995).

from studies that inadequately represent average forest conditions, (2) modeling errors (erroneous assumptions), and (3) errors in converting estimates from one reporting unit to another (Birdsey and Heath 1995). In particular, the impacts of forest management activities, including harvest, on soil carbon are not well understood. Moore et al. (1981) found that harvest may lead to a 20 percent loss of soil carbon, while little or no net change in soil carbon following harvest was reported in another study (Johnson 1992). Since forest soils contain over 50 percent of the total stored forest carbon in the United States, this difference can have a large impact on flux estimates.

The third source of uncertainty results from the use of projections of forest carbon stocks for the year 2000 (Birdsey and Heath 1995) to estimate annual net carbon sequestration from 1993 to 1997. These projections are the product of two linked models (FORCARB and TAMM/ATLAS) that integrate multiple uncertain variables related to future forest growth and economic forecasts. Because these models project decadal rather than annual carbon fluxes, estimates of annual net carbon sequestration from 1993 to 1997 are calculated as *average* annual estimates based on projected long-term changes in U.S. forest stocks.

The fourth source of uncertainty results from incomplete accounting of wood products. Because the wood product stocks were estimated using U.S. harvest statistics, these stocks include exports, even if the logs were processed in other countries, and exclude imports. Haynes (1990) estimates that imported timber accounts for about 12 percent of the timber consumed in the United States, and that exports of roundwood and primary products account for about 5 percent of harvested timber.

Changes in Non-Forest Soil Carbon Stocks

The amount of organic carbon contained in soils depends on the balance between inputs of photosynthetically fixed carbon (i.e., organic matter such as decayed detritus and roots) and loss of carbon through decomposition. The quantity and quality of organic matter inputs, and the rate of decomposition, are determined by the combined interaction of climate, soil properties, and land-use. Agricultural practices and other land-use activities, such as clearing, drainage, tillage, planting, crop residue management, fertilization, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net flux of carbon dioxide (CO_2) to or from soils. The addition of carbonate minerals to soils through liming operations also results in net emissions of CO_2. Changes in non-forest soil carbon stocks include net fluxes of CO_2 from three categories of land-use/land-management activities: (1) activities on organic soils, especially cultivation and conversion to pasture and forest; (2) activities on mineral soils, especially land-use change activities; and (3) liming of soils.[6] Organic soils and mineral soils are treated separately because each responds differently to land-use practices.

Organic soils contain extremely deep and rich layers of organic matter. When these soils are cultivated, tilling or mixing of the soil brings buried organic matter to the soil surface, thereby accelerating the rate of decomposition and CO_2 generation. Because of the depth and richness of the organic layer, carbon loss from cultivated organic soils can be sustained over long periods of time (IPCC/UNEP/OECD/IEA 1997). Conversion of organic soils to agricultural uses typically involves drainage as well, which also exacerbates soil carbon oxidation. When organic soils are disturbed, through cultivation and/or drainage, the rate at which organic matter decomposes, and therefore the rate at which CO_2 emissions are generated, is determined primarily by climate, the composition (decomposability) of the organic matter, and the specific land-use practices undertaken. The use of organic soils for upland crops results in greater carbon loss than conversion to pasture or forests, due to deeper drainage and/or more intensive management practices (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997).

Mineral soils generally have fairly shallow organic layers and therefore have low organic carbon contents

[6] Fluxes of CO_2 from forest soils are excluded from this source because they are included in the previous source category (Changes in Forest Carbon Stocks).

relative to organic soils. Consequently, it is possible to entirely deplete the carbon stock of a mineral soil within the first 10 to 20 years of disturbance, depending on the type of disturbance, climate, and soil type. Once the majority of the native carbon stock has been depleted, an equilibrium is reached that reflects a balance between accumulation from plant residues and loss of carbon through decomposition. Various land-use practices, such as incorporation of crop residues and cultivation of certain crops, can result in a net accumulation of carbon stocks in mineral soils.

Lime in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) is commonly added to agricultural soils to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate of degradation is determined by soil conditions and the type of mineral applied; it can take several years for agriculturally-applied lime to degrade completely.

Only two categories of land-use/land-management activities—agricultural use of organic soils and liming—are included in the estimates of CO_2 emissions presented here, because insufficient activity data were available to estimate fluxes from mineral soils. Net annual emissions of CO_2 from organic soils and liming of soils in the United States over the period 1990 through 1997 totaled approximately 8 to 9 MMTCE (30 to 32 Tg) (see Table 6-6 and Table 6-7).

Table 6-6: CO_2 Flux From Non-Forest Soils (MMTCE)

Year	Mineral Soils	Organic Soils	Liming of Soils
1990	NA	5.9	2.2
1991	NA	5.9	2.8
1992	NA	5.9	2.1
1993	NA	5.9	2.1
1994	NA	5.9	2.3
1995	NA	5.9	2.5
1996	NA	5.9	2.4
1997	NA	5.9	2.8

NA (Not Available)
Note: The CO_2 flux from non-forest soils has been excluded from the total flux reported for the Land-Use Change and Forestry chapter due to the high level of uncertainty associated with these estimates.

Table 6-7: CO_2 Flux From Non-Forest Soils (Tg CO_2)

Year	Mineral Soils	Organic Soils	Liming of Soils
1990	NA	21.8	8.2
1991	NA	21.8	10.2
1992	NA	21.8	7.8
1993	NA	21.8	7.7
1994	NA	21.8	8.5
1995	NA	21.8	9.3
1996	NA	21.8	8.9
1997	NA	21.8	10.4

NA (Not Available)
Note: The CO_2 flux from non-forest soils has been excluded from the total flux reported for the Land-Use Change and Forestry chapter due to the high level of uncertainty associated with these estimates.

Annual CO_2 emissions from agricultural use of organic soils were estimated to be 5.9 MMTCE (21.8 Tg) over the 1990 through 1997 period. Organic soil data were available for only 1982; therefore, emissions from organic soils were assumed to stay constant at the 1982 level for the years 1990 to 1997. Liming accounted for net annual CO_2 emissions of approximately 2.1 to 2.8 MMTCE (8 to 10 Tg). There was no apparent trend over the seven year period.

The emission estimates and analysis for this source are restricted to CO_2 fluxes associated with the management of non-forest organic soils and liming of soils. However, it is important to note that land-use and land-use change activities may also result in fluxes of non-CO_2 greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO), to and from soils. For example, when lands are flooded with freshwater, such as during hydroelectric dam construction, CH_4 is produced and emitted to the atmosphere due to anaerobic decomposition of organic material in the soil and water column. Conversely, when flooded lands, such as lakes and wetlands, are drained, anaerobic decomposition and associated CH_4 emissions will be reduced. Dry soils are a sink of CH_4, so eventually, drainage may result in soils that were once a source of CH_4 becoming a sink of CH_4. However, once the soils become aerobic, oxidation of soil carbon and other organic material will result in elevated emissions of CO_2. Moreover, flooding and drainage may also affect net soil fluxes of N_2O and CO, although these fluxes are highly uncertain. The fluxes of CH_4, and other gases, due to flooding and drainage are not assessed in this inventory due to a lack of activity data on the extent of these practices in the United States as well as scientific uncertainties about the variables that control fluxes.[7]

Methodology and Data Sources

The methodologies used to calculate CO_2 emissions from cultivation of organic soils and liming follow the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

To estimate annual CO_2 emissions from organic soils, the area under agricultural usage was divided into broad climatic regions, and the area in each climatic region was multiplied by an emission factor. (All areas were cropped rather than utilized for pasture or forestry, so there was no need to further divide areas into general land-use types). Annual statistics on the area of organic soils under agricultural usage were not available for the years 1990 through 1997; therefore, an estimate for the area cultivated in 1982 (Mausbach and Spivey 1994) was used for all years in the 1990 to 1997 series. The area estimate was derived from USDA land-use statistics.[8] Of the 850,000 hectares of organic soils under cultivation in 1982, Mausbach and Spivey (1994) estimated that two-thirds were located in warm, temperate regions and one-third was located in cool, temperate regions (see Table 6-8). The IPCC default emission factors (10 metric tons C/hectare/year for warm, temperate regions, 1.0 metric tons C/hectare/year for cool, temperate regions) were applied to these areas to estimate annual CO_2 emissions resulting from cultivation of organic soils.

Carbon dioxide emissions from degradation of limestone and dolomite applied to agricultural soils were calculated by multiplying the annual amounts of limestone and dolomite applied, by CO_2 emission factors (0.120 metric ton C/metric ton limestone, 0.130 metric ton C/metric ton dolomite).[9] These emission factors are based on the assumption that all of the carbon in these materials evolves as CO_2. The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey's Mineral Resources Program Crushed Stone Reports and Mineral Industry Surveys (USGS 1998a, 1998b, 1997a, 1997b, 1996, 1995, 1993). To develop these data, the Mineral Resources Program obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, the estimates of total crushed limestone and dolomite production and use are divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production). To estimate the total amounts of crushed limestone and dolomite applied to agricultural soils, it was assumed

Table 6-8: Areas of Cultivated Organic Soils and Quantities of Applied Minerals

Description	1990	1991	1992	1993	1994	1995	1996	1997
Organic Soils Area Cultivated (hectares)								
Warm Temperate Regions	566,000	566,000	566,000	566,000	566,000	566,000	566,000	566,000
Cool Temperate Regions	284,000	284,000	284,000	284,000	284,000	284,000	284,000	284,000
Applied Minerals (Gg)								
Limestone	16,063	19,820	15,268	15,340	16,730	18,244	17,479	20,286
Dolomite	2,402	3,154	2,283	2,040	2,294	2,751	2,499	3,034

[7] However, methane emissions due to flooding of rice fields are included. These are addressed under Rice Cultivation in the Agriculture chapter.

[8] This estimate does not include Alaska, but the area of cultivated organic soils in Alaska is believed to be small and emissions per unit area in colder regions are relatively low, so this omission is probably quite minor. The estimate also does not include U.S. territories.

[9] Note: the default emission factor for dolomite provided in the Workbook volume of the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) is incorrect. The value provided is 0.122 metric ton carbon/ metric ton of dolomite; the correct value is 0.130 metric ton carbon/ metric ton of dolomite.

that the fractions of "unspecified" and "estimated" production that were applied to agricultural soils were equal to the fraction of "specified" production that was applied to agricultural soils. In addition, the total crushed limestone and dolomite production figures for 1991, 1993, 1994, and 1995 were revised by the Mineral Resources Program in later reports, but end uses were not specified. To estimate the amounts applied to agricultural soils, it was assumed that the fractions estimated using the previously published data did not change.

Uncertainty

Uncertainties in the emission estimates presented result primarily from the underlying activity data used in the calculations. In particular, statistics on the areas of organic soil cultivated or managed as pasture or forest were not available, and the point estimate of total organic soil cultivated is highly uncertain. In addition, the breakdown of the cultivated organic soil area by climate region was based upon a qualitative assessment of the location of cultivated organic soils. Furthermore, there are uncertainties in the estimates of total limestone and dolomite applied to agricultural soils, which are based on estimates as well as reported quantities.

The emission factors used in the calculations are an additional source of uncertainty. As discussed above, CO_2 emissions from cultivation of organic soils are controlled by climate, the composition of the soil organic matter, and cultivation practices. Only the first variable is taken into account, and only in a general way, in deriving the emission factors. Moreover, measured carbon loss rates from cultivated organic soils vary by as much as an order of magnitude.

The rate of degradation of applied limestone and dolomite is determined by soil conditions and the type of mineral applied. It can take several years for agriculturally-applied lime to degrade completely. The approach used to estimate CO_2 emissions from liming assumed that the amount of mineral applied in any year was equal to the amount that degrades in that year, so annual application rates could be used to derive annual emissions; however, this assumption may be incorrect. Moreover, soil conditions were not taken into account in the calculations.

Because the estimates of CO_2 fluxes from non-forest soils are based on limited and highly uncertain activity data and cover only a subset of the CO_2 fluxes associated with this source, the estimate of CO_2 flux from non-forest soils has been excluded from the total flux reported for the Land-Use Change and Forestry chapter.